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OPTICAL, MAGNETIC, AND RADIO MEASUREMENTS IN SUPPORT OF THE OOSIK EXPERIMENT

George B. Carpenter

Stanford Research Institute

Final Report August 1972

OPTICAL, MAGNETIC AND RADIO MEASUREMENTS IN SUPPORT OF THE OOSIK EXPERIMENT
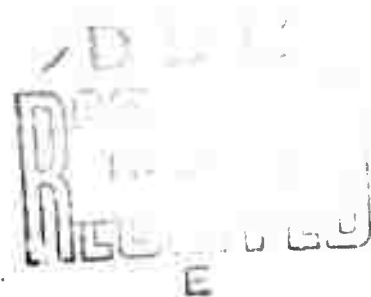
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13. ABSTRACT

At 0659 GMT March 7, 1972 a shaped barium charge was released high above central Alaska by the Los Alamos Scientific Laboratory and the University of Alaska. In support of this experiment, known as OOSIK, the Stanford Research Institute operated two existing radar facilities in Alaska. In addition, a low-frequency receiving site was established and operated near the point at which the field line through the barium release intercepted the ground. The most striking feature of the data recorded during the OOSIK experiment is the occurrence of a magnetic substorm 17 minutes after the barium injection. Considerable visible and radar aurora accompanied the substorm. A number of factors strongly indicate that the substorm was of natural origin. Among these factors is a comparison of the plasma density required to initiate a magnetospheric instability and the density achieved by the OOSIK injection. Population of multiple field lines by OOSIK apparently reduced the density in any one flux tube far below that required to initiate an instability at the local time of injection. If the problem of multiple population can be avoided during an early-morning launch when magnetospheric conditions are favorable, it seems likely that an instability can be triggered by a rocket-launched shaped barium charge.

Details of illustrations in
this document may be better
studied on microfiche.

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At 0659 GMT March 7, 1972 a shaped barium charge was released high above central Alaska by the Los Alamos Scientific Laboratory and the University of Alaska. In support of this experiment, known as OOSIK, the Stanford Research Institute operated two existing radar facilities in Alaska. In addition, a low-frequency receiving site was established and operated near the point at which the field line through the barium release intercepted the ground. The most striking feature of the data recorded during the OOSIK experiment is the occurrence of a magnetic substorm 17 minutes after the barium injection. Considerable visible and radar aurora accompanied the substorm. A number of factors strongly indicate that the substorm was of natural origin. Among these factors is a comparison of the plasma density required to initiate a magneto-spheric instability and the density achieved by the OOSIK injection. Population of multiple field lines by OOSIK apparently reduced the density in any one flux tube far below that required to initiate an instability at the local time of injection. If the problem of multiple population can be avoided during an early-morning launch when magneto-spheric conditions are favorable, it seems likely that an instability can be triggered by a rocket-launched shaped barium charge.

CONTENTS

ILLUSTRATIONS

TABLES

ACRONYMS, SYMBOLS, AND ABBREVIATIONS

$\overset{\circ}{A}$	Angstrom unit, 10^{-10} meters
AFCRL	Air Force Cambridge Research Laboratory
ARPA	Defense Advanced Research Projects Agency
B	Magnetic flux density
cm	Centimeter
dB	Decibel
DNA	Defense Nuclear Agency
el	Electron
eV	Electron volt (1.602×10^{19} joules)
FM	Frequency modulation
GMT	Greenwich Mean Time
Hz	Hertz, one cycle per second
hr	Hour
kHz	Kilohertz, 1000 hertz
km	Kilometer, 1000 meters
km/s	Kilometer per second, 1000 meters per second
kW	Kilowatt, 1000 watts
L	Geocentric distance to the top of an earth's field line in multiples of the earth's radius
L-Band	About 800 to 1600 megahertz
LASL	Los Alamos Scientific Laboratory
LF	Low frequency, 30 to 300 kilohertz
MHz	Megahertz
mm	Millimeter
m/s	Meters per second
mV/m	Millivolt per meter

MW	Megawatt
N	North
NASA	National Aeronautics and Space Administration
PC5	Oscillatory variation of the earth's field with period from 150 to 600 seconds
PM	Post-meridian local time
PRF	Pulse-repetition frequency
R	Release time
RTI	Range-time-intensity
s	Second
SRI	Stanford Research Institute
TMA	Tri methyl aluminum
UA	University of Alaska (Geophysical Institute)
ULF	Ultra low frequency, less than 30 hertz
UHF	Ultra high frequency, 300 to about 800 megahertz
VCO	Voltage-controlled oscillator
VLF	Very low frequency, 3 to 30 kilohertz
VHF	Very high frequency, 30 to 300 megahertz
W	West
o	Degree
γ	Gamma, unit of magnetic-field density
μs	Microsecond

ACKNOWLEDGMENTS

I SUMMARY

Recent theoretical investigations by Brice[1,2*] and by Cornwall,[3,4] among others, have suggested that artificial injection of a relatively small amount of cold plasma into the magnetosphere can lead to instabilities. An increase in cold-plasma density leads to a change in the number of particles that can be stably trapped in the earth's radiation belt. The excess is precipitated into the atmosphere as the result of pitch-angle modification. Amplification of ULF and VLF radio waves can accompany the instability. Particle precipitation and wave amplification may have military importance if they can be controlled. Both of these subjects are being studied by a number of organizations under sponsorship of the Defense Advanced Research Projects Agency (ARPA). Stanford Research Institute (SRI) is one of the participants in this study, and a more detailed discussion of magnetospheric instabilities and their application is given in an Interim Technical Report[5] on Contract N00014-72-C-0402.

An opportunity to test magnetospheric instability theories arose in March 1972 when the Los Alamos Scientific Laboratory (LASL) and the University of Alaska (UA) announced plans to fire a shaped barium charge along the earth's magnetic field high above central Alaska. Extensive optical measurements were planned by these two organizations, but if the results of a triggered magnetospheric instability were to be observed, radar and radio-wave measurements would have to be carried out. The Defense Advanced Research Projects Agency contracted with the Stanford Research Institute to carry out these measurements. Arrangements were

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* References are listed at the end of the report.

made to operate the VHF/UHF/L-band radar at Homer, Alaska and the L-band radar at Chatanika, Alaska.[*] Radio-wave and magnetic sensors were installed and operated at Venetie, Alaska near the down-field location of the barium release. The instrumentation and experimental plan are discussed in Section III of this report.

The OOSIK shaped barium charge was released approximately 0659 GMT, March 7, 1972 at an altitude of 538 to 544 km on an L shell of about 6.75. After several minutes a number of adjacent field lines were observed to be populated by barium ions. As many as eight different lines were populated at times greater than 10 min. Magnetic and auroral conditions were active prior to the release but were relatively quiet during the release and for an additional 17 min. Optical tracking of the populated field line indicates that the barium plasma moved to the southeast about 400 m/s. A more detailed description of the launch and release is given in Section IV.

Seventeen minutes after the barium release a sudden-commencement magnetic perturbation was observed over a wide geographic area. The cryogenic magnetometer at Venetie showed the excursion to have been at least as great as 320 Y in 11 min. The initial positive excursion lasted only about 20 min, while the subsequent negative bay lasted over an hour. Considerable auroral activity accompanied the magnetic substorm. Weak aurora visible far to the south of Venetie became much brighter and more active as it moved north. Between 0722 and 0726 GMT aurora formed overhead at Venetie. A fairly narrow arc of aurora extending from the eastern to western horizon remained near the magnetic zenith at Venetie for more than half an hour. A very dramatic auroral

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[*] The Chatanika observations were carried out as a part of the research program sponsored then by the Defense Nuclear Agency, under Contract DNA001-72-C-0076. Both the Chatanika and Homer radars are DNA facilities.

display was centered at the magnetic zenith where tens of minutes earlier the barium had been released. Radar aurora observed from Homer was not well correlated with visible aurora before the substorm. Radar returns were received from the test area prior to and following the release, although none was visible from Venetie. The correlation was much better following the substorm. The Chatanika radar observed large ionospheric drift velocities prior to the barium release. Comparable data were not obtained after the release but it is assumed that drifts were still large because of their direct correlation with magnetic activity. Section V contains a complete description of the experimental data obtained.

In evaluating the data we must decide whether the magnetic substorm and auroral display were produced by a triggered magnetospheric instability, whether they were natural and masked a triggered instability, or whether they were natural and there was no triggered instability. Several factors suggest that the substorm at R + 17 min was natural. Its wide geographic extent is highly indicative of this, and it occurred when the barium ions had ascended less than one-third of the way to the equatorial crossing of the field line where instabilities would most likely be triggered. A theoretical formulation by Brice and Lucas has been evaluated in Section VI to show that injection of cold plasma in the equatorial plane leading to a density in excess of 2.5 el cm^{-3} may initiate an instability when proper conditions exist in the magnetosphere in the morning. Density increases in excess of 10 el cm^{-3} are required to produce nighttime instabilities. The density increase achieved at the magnetic equator by the OOSIK barium release may not have been more than about 1 el cm^{-3} because of a separation of barium ions into a number of different flux tubes. Without this separation the density might have been as much as 7 el cm^{-3} at the magnetic equator, enough to produce instability under morning and possibly some nighttime conditions. Two conclusions are drawn:

3

(1) Shaped-charge releases appear capable of adding sufficient cold plasma in the equatorial plane to cause magnetospheric instability under favorable magnetospheric conditions.

(2) The OOSIK barium release probably did not produce a magnetospheric instability.

Two recommendations are made in this report:

(1) The mechanism responsible for the separation of the OOSIK barium jet into a number of different flux tubes should be identified.

(2) Additional measurements should be conducted during two shaped-charge releases planned for Alaska in October 1972.

Conclusions and recommendations are contained in Section VII.

4

II INTRODUCTION

Energetic particles trapped in the earth's magnetic field are estimated to store 10^{15} J of energy. Very little practical use has been made of this energy since the radiation belts were discovered by Van Allen[8] in 1958. Perhaps this will change as the result of recent work by Brice[1,2] and by Cornwall.[3,4] Their investigations suggest that when certain conditions exist in the magnetosphere, instabilities can be initiated by artificial injection of cold plasma. Triggering of instabilities can lead to useful control of wave amplification in the magnetosphere and precipitation of particles into the atmosphere. Both of these phenomena are known to occur naturally and may have military application if controlled. Natural wave amplification is manifested in certain features of whistler and micropulsation propagation. Natural precipitation has been discovered to be responsible for localized absorption regions in the ionosphere.

An opportunity to test the Brice/Cornwall theories became available in the early months of 1972. Los Alamos Scientific Laboratory (LASL) and the University of Alaska (UA) jointly announced that a shaped barium charge would be released high above Central Alaska in March 1972. The experiment, to be known as OOSIK, would be a continuation of a joint LASL/UA program to utilize the photoionization property of barium to map magnetic field lines. The technical and logistical feasibility of mapping field lines had been proven in October 1971 when two shaped charges[7] were released above Kauai on low-latitude field lines. The Kauai tests, known as ALCO and BUBIA, were part of Operation BARBIZON and were successful in populating an entire flux tube with barium ions.

Extensive optical measurement of OOSIK was planned by LASL/UA. If OOSIK succeeded in placing sufficient cold plasma in the magnetosphere to trigger instabilities, its occurrence would best be detected by radio and radar measurements. The Defense Advanced Research Projects Agency contracted with the Stanford Research Institute to provide such measurements. The instrumentation fielded by SRI during OOSIK is described in Section III of this report. The OOSIK launch and release are described in Section IV and the results obtained are presented in Section V. An evaluation of the data is presented in Section VI, followed by conclusions and recommendations in Section VII.

6

III INSTRUMENTATION

A. VHF/UHF/L-Band Radars

In planning the SRI experimental program for OOSIK, two problems
had to be addressed: where to establish field sites and what instru-
ments to deploy. In the case of high-power, large-aperture radars,
the location are fixed. Two such radars were available in Alaska, a
VHF/UHF/L-band auroral-clutter radar at Homer, and an L-band incoherent-
scatter radar at Chatanika. Both of these Defense Nuclear Agency radars
are capable of viewing the nominal OOSIK release location, announced to
be 66.12°N, 147.61°W, and 539 km altitude. The Homer radar views the
area very nearly at perpendicular incidence to the local magnetic field
and is thus sensitive to field-aligned targets. The Chatanika radar
lies more nearly under the nominal release location. The relative loca-
tions of the radars and release point are shown in Figure 1. Contours
i Figure 1 indicate the deviation from perpendicular incidence to the
magnetic field at an altitude of 120 km for transmissions from the Homer
radar. The decision to operate the Alaska radars required that two
operators be sent to the Homer site; operators were already at Chatanika
carrying out research programs.

The Homer radar was manned from 2 to 18 March and operated during the
launch of several experimental rockets in addition to OOSIK. Pulses of
300 μs duration at a PRF of 75 were radiated at three frequencies--139,
398, and 1210 MHz. The 3-dB beamwidths are approximately 9°, 3°, and 1°.
The peak transmitted powers were roughly 7, 40, and 40 kW, respectively.
Doppler and video data were recorded on tape at the following times:

7
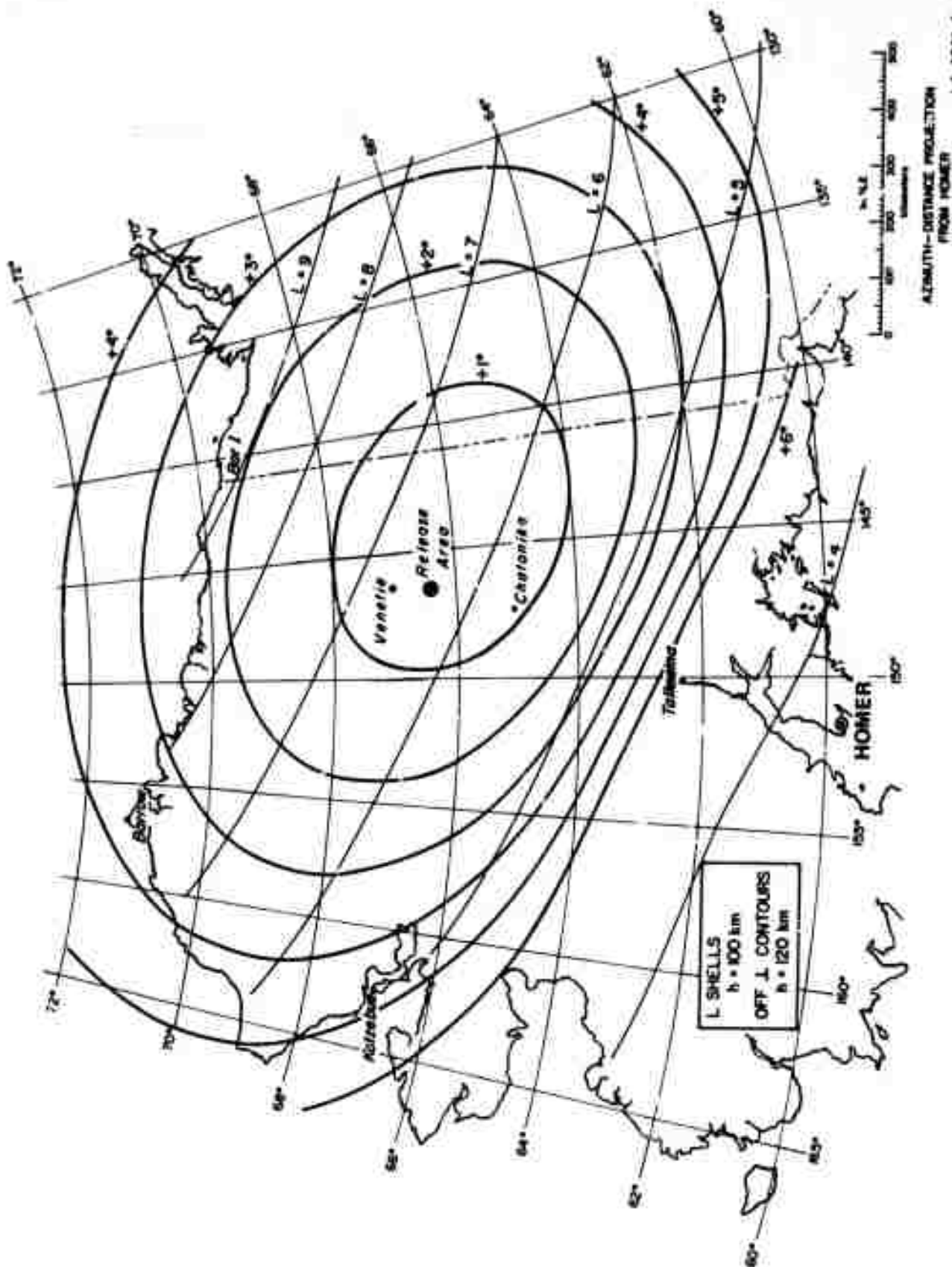
FIGURE 1 BARIUM RELEASE AND FIELD-SITE LOCATIONS

- 6 March   0926 to 0958 GMT

              1215 to 1258 GMT   AFCRL Astrobee (1214 GMT)

- 7 March   0514 to 0559 GMT   NASA barium puffs (0516 GMT)

              0653 to 0727 GMT   LASL/UA COSIK (0652 GMT)

              0740 to 0819 GMT   Aurora

              0825 to 0832 GMT   Aurora

              0859 to 0934 GMT   Satellite pass

              1430 to 1515 GMT   NASA barium puffs (1426 GMT)

- 9 March   0820 to 0830 GMT   Aurora

              0853 to 0900 GMT   Aurora

              1036 to 1059 GMT   AFCRL Astrobee (1052 GMT)

              1108 to 1134 GMT   Aurora

              1408 to 1423 GMT   NASA barium puffs (1408 GMT)

- 10 March   0908 to 0931 GMT   Satellite pass

- 11 March   0712 to 0820 GMT   Aurora

- 14 March   0830 to 0845 GMT   Aurora

- 15 March   1055 to 1136 GMT   Aurora

              1217 to 1238 GMT   Aurora

- 16 March   0748 to 0807 GMT   Aurora

              0954 to 1036 GMT   LASL Terrier-Sandhawk (0954 GMT)
                                    AFCRL Black Brant (1010 GMT)

- 17 March   0940 to 1013 GMT   LASL Terrier-Sandhawk (0939 GMT)

The Chatanika L-band radar operates routinely, studying geophysical phenomena of interest to the Defense Nuclear Agency. This facility operated in conjunction with a number of rocket launches from Poker Flat in March 1972. The nominal characteristics of the facility are described in a paper by Leadabrand et al.[8] Pulses of 320- and 67-μs duration were

9

alternately radiated at 1290 MHz at a PRF of 75. The 3-dB beamwidth is approximately 0.6°. The peak power was of the order of 3 MW. Data were recorded at the following times:

- 4 March   0352 to 1149 GMT   Drift velocities

- 5 March   0410 to 0429 GMT   Drift velocities

- 6 March   0402 to 1227 GMT   AFCRL Astrobee (1214 GMT)
                                          Drift velocities
                                          Satellite pass
            1245 to 1442 GMT   Drift velocities

- 7 March   0415 to 1133 GMT   NASA barium puffs (0516 GMT)
                                          LASL/UA OOSIK (0652 GMT)
                                          Satellite pass
            1159 to 1600 GMT   NASA barium puffs (1426 GMT)
                                          Drift velocities

- 8 March   0616 to 1705 GMT   Drift velocities

- 9 March   0435 to 1533 GMT   AFCRL Astrobee (1052 GMT)
                                          Drift velocities
                                          NASA barium puffs (1408 GMT)

- 10 March   0447 to 1906 GMT   Satellite pass
                                          6300-Å comparison

- 11 March   0723 to 0922 GMT   Aurora
            0938 to 1201 GMT   Aurora

- 12 March   0514 to 1600 GMT   6300-Å comparison

- 13 March   0400 to 2400 GMT   24-hr drift velocities

- 14 March   0000 to 0439 GMT   24-hr drift velocities
            0731 to 1159 GMT   Holding for rockets

- 15 March   0444 to 0457 GMT   Holding for rockets
            0744 to 1032 GMT   Holding for rockets
            1055 to 1240 GMT   Holding for rockets

- 16 March   0738 to 1053 GMT   LASL Terrier-Sandhawk (1016 GMT)
  AFCRL Black Brant (0954 GMT)

- 17 March   0659 to 0709 GMT   Drift velocities

                0723 to 0930 GMT   Drift velocities

                0939 to 1129 GMT   LASL Terrier-Sandhawk (0939 GMT)

- 18 March   0514 to 1208 GMT   Utah State U. Apache (0903 GMT)

B. Electromagnetic, Magnetic, and Optical Sensors

A number of low-frequency receiving systems were available at SRI
for possible deployment during OOSIK. Of these, two systems were
selected—a three-channel broadband system and a multifunctioned satel-
lite backup receiving system. The three-channel broadband system covered
the frequency range 1 to 100 kHz and employed two crossed loops and a
vertical whip as sensors. The satellite receiver operates from a single
loop sensor and broadband preamplifier providing six outputs: (1) broad-
band amplitude 200 Hz to 12.5 kHz, (2) narrowband amplitude from a filter
sweeping 200 Hz to 1.6 kHz, (3) narrowband amplitude from a filter sweep-
ing 1.6 kHz to 12.5 kHz, (4) narrowband amplitude from a filter sweeping
12.5 to 100 kHz, and (5) narrowband amplitude (on a selected frequency),
and (6) phase of the frequency selected in (5).

Low-frequency signals generated as a result of OOSIK most likely
would originate somewhere along the magnetic field line passing through
the release. The ideal location for the receiving system was therefore
at the foot of the field line; this location was estimated from a multi-
coefficient computer model of the field. The nominal earth intersection
of the line was computed to be at 66.96°N, 146.63°W, approximately 11 km
southwest of Venetie, Alaska.

Arrangements were made with the tribal council of this small Indian
village to rent the community hall to house our instruments. The location

of this village is shown in Figure 1. The coordinates are 67° 00.9'N, 146° 24.6'W.

The merits of fielding a magnetometer for OOSIK were discussed at length. If a magnetometer was to be taken to Venetie it would have to have exceptional sensitivity, and such sensitivity can be achieved only with cryogenic sensors. To this end, a single-axis cryogenic magnetometer was leased from the Develco Corporation of Mountain View, California. A consultant from Develco accompanied three SRI field personnel to Venetie to ensure that the magnetometer would function in such a hostile environment. Important characteristics of instruments fielded at Venetie for OOSIK are listed in Table 1.

Table 1

MEASUREMENTS AT VENETIE

3-Channel Broadband System

E_v: Vertical electric component of wavefront.
1 kHz to 100 kHz direct recorded on tape.

H_p: Horizontal magnetic field component parallel
to the earth's magnetic meridian. 0.4 to 100
kHz direct recorded on tape. Equivalent sensi-
tivity approximately 0.3 to 30 mV/m.

H_t: Horizontal magnetic-field component transverse
to the earth's magnetic meridian. 0.4 to 100 kHz
direct recorded on tape. Equivalent sensitivity
approximately 0.3 to 30 mV/m.

Table 1 (continued)

Multichannel Receiver

Input: H_t signal from broadband system.

Outputs:

- 0.4 to 12.5 kHz broadband direct recorded.

- 3 narrowband stepping-filter outputs applied to voltage-controlled oscillators (VCOs) and direct recorded. The three filters step simultaneously through the bands 0.4 to 1.6 kHz, 1.6 to 12.5 kHz, and 12.5 to 100 kHz. There are 256 steps in each band. Minimum sweep period is about 3.5 s.

- Amplitude of signal in a tunable narrowband filter applied to a VCO and recorded directly.

- Phase of signal in a tunable narrowband filter applied to a VCO and recorded directly.

Cryogenic Magnetometer (Develco Corporation)

- Axis of sensing coil at 45° elevation and 45° from magnetic meridian.

- Sensitivity linear from 0 to -80 dB relative to 1 gamma.

- 0-to-80 Hz frequency response FM recorded on magnetic tape.

Cameras

Three 35-mm cameras on tripods. High-speed black-and-white film was used in one, and high-speed color film in the other two. The black-and-white film advance and shutter release were controlled automatically by timers.

The Venetie site became operational in stages. The low-frequency receiving systems arrived on March 1, and were marginally operational by March 3, the earliest possible COSIK launch date. Data recorded the evening of March 3 (March 4 GMT) were severely contaminated by interference from the local power-generation system. On March 4, ground

loops in the receiving instrumentation were eliminated, reducing the hum level. The magnetometer arrived March 4 and was marginally operational by 8:30 PM that evening. The daylight hours of March 5 were spent reducing the power-system interference and placing the sensor for the magnetometer in a remote snow bank. The main ground connection on the diesel-generator power system was found to be loose and was replaced. In addition, a separate ground wire was provided for our receiving equipment. A substantial reduction in power-line noise permitted the gains of the antenna preamplifiers to be increased. The saturation level of the magnetic field channels was approximately equal to 30 mV/m. The receiving systems at Venetie remained unchanged until March 9 when they were dismantled and shipped home. Data were obtained at the following times:

- March 4   0437 to 0540 GMT

- March 5   0638 to 0741 GMT

- March 6   0440 to 0543 GMT
              0738 to 0841 GMT

- March 7   0505 to 1030 GMT   Barium puffs and OOSIK

- March 7   1400 to 1605 GMT   Barium puffs

- March 8   0445 to 0755 GMT

- March 8   1338 to 1543 GMT

- March 9   0456 to 0550 GMT

- March 9   1350 to 1520 GMT   Barium puffs

IV LAUNCH AND RELEASE DESCRIPTION

At least five constraints dictated the time of launch of the
OOSIK shaped charge. The most important requirement was that the sun
illuminate the release point to cause photoionization. Almost as
important was the necessity that the earth's surface be dark to facili-
tate optical measurements. These two constraints dictated establishment
of ten-minute launch windows shortly after ground sunset. Optical
measurements would not be successful if the moon were visible or if the
weather were bad, hence the third and fourth constraints. The moon
location dictated a launch interval from 3 March to 15 March. The
final constraint was the desire for quiet magnetic conditions.

The first possible launch window the evening of 3 March was used
as a dry run to evaluate the coordination of the many experiments and
experimenters. Launches on 4, 5 March were canceled by bad weather.
Weather was not a problem on 6 March, but magnetic activity was.
During the early part of the evening auroral arcs repeatedly moved
down from the north and through the test area. The magnetic activity
was suitable for electric-field measurements in the ionosphere by means
of barium puffs. Four puffs were released at intervals along a rocket
trajectory at about 0518 to 0523 GMT (7 March). Magnetic and auroral
activity lessened as the OOSIK launch window approached, but not to an
acceptable degree. The launch was held through the nominal window and
placed on a minute-by-minute status because of the prospect of unsuitable
weather for several days. Magnetic activity was deemed tolerable at
0653 GMT and OOSIK was launched.

At 659 GMT, 7 March, the OOSIK rocket achieved alignment with the earth's magnetic field and the shaped charge was fired. The altitude at release time is estimated to have been from 538 to 544 km. The 538-km value comes[9] from extrapolation of radar tracking data, while 544 km is the result[10] of photographic triangulation by the University of Alaska. The subrelease point based on the radar data is 66.42°N, 147.58°W, compared to 66.33°N, 147.52°W for the UA triangulation. Using 544-km altitude and photographs taken at Venetie we have estimated the subrelease point to be 66.51°N. 147.54°W. The estimate based on photographic data at Venetie is not strongly dependent on the release-altitude estimate, and it may be more reliable. The magnetic field line through the release coordinates intersects the earth at 67.35°N, 146.37°W, only 37 km north of Venetie. The L value is about 6.75.

At the instant of release, the 881-gram barium liner of the shaped charge was compressed to such a degree that barium-vapor velocities of greater than 10 km/s were achieved. Optical tracking of barium ions guided up along the field indicates preferred velocities of approximately 12 and 14 km/s. Although the barium ions initially began life on a field line near Venetie, they develop a horizontal drift to the south and east at a velocity near 400 m/s. By R + 19 min the earth intersect of populated magnetic flux tubes was reported[10] to be near 64°N, 144°W. The ions did not stay confined to a single flux tube. Within minutes, several adjacent flux tubes were populated, and by R + 15 min as many as eight distinct tubes were populated. There is some indication that barium ions reached the equatorial plane nearly an hour after injection. Very sensitive optical instruments in Washington State provide this information.

V EXPERIMENTAL OBSERVATIONS

A. Observations at Venetie

1. Visual Observations

The visual sights above Venetie very much impressed those
present the evening of March 6 (March 7 GMT). The account given below
relies on three sources of information: the memory of the field-site
operating staff, photographs taken at various times, and tape-recorded
verbal descriptions. Memory indicates that during the early evening,
auroral arcs repeatedly moved down from the north, through the test
area, and remained faintly visible near the southern horizon. A series
of barium puffs was released shortly after 0500 GMT when auroral activity
was still visible in the sky. The photographic coverage of this series
of puffs was minimal. Personnel were indoors during the first puff and
had cameras operating only during the last barium puff and the TMA
release.

Visual auroral activity appeared diminished following the puff
releases. Faint green aurora was evident in the southern sky as the
OOSIK launch window approached; the release point overhead was completely
clear. At 0659 GMT a yellow-green spot appeared overhead and quickly
grew to the size and brightness of the full moon. A finger of pink ions
emerged from the neutral cloud and appeared to move up the magnetic
field. Black and white and color photographs were taken at frequent
intervals. An example is shown in Figure 2. After several minutes
the neutral cloud was no longer visible, leaving a very faint pink glow
generally aligned with the magnetic field. There was little visual
evidence of the OOSIK release at times greater than R + 5 min and

17

FIGURE 2   OOSIK BARIUM SHAPED CHARGE SOON AFTER RELEASE

18

personnel went indoors to dispel the -30°F chill. When they returned at about R + 17, the southern aurora appeared closer, brighter, and more active. A verbal description of the auroral display was tape-recorded for nearly an hour. Color photographs were taken periodically until the last camera froze.

At 0722 GMT there were three curtains of bright green aurora to the southeast and several irregular shaped curtains to the southwest. Striated sheets of aurora formed nearly overhead between 0722 and 0726 GMT. Its character did not seem particularly unusual except that the color to the south seemed more red than to the north. The auroral display from 0727 to about 0800 GMT did seem unusual. During this period the magnetic zenith overhead was the focal point for a very dazzling visual display. During most of this period a very narrow (at some times as little as a few degrees wide) arc remained overhead and extended from the eastern horizon to the western horizon. No aurora was visible to the north and only faint green aurora was seen to the south. Considerable activity was seen at the magnetic zenith and frequent changes in color were evident. Various tinges of red, white, and green were present. In the example shown in Figure 3 the red is emphasized by the film more than was visible to the eye. It should be remembered that during this dramatic display at the magnetic zenith, the magnetic flux tubes populated by barium ions had moved far to the south and east.

Extremely good photographs were obtained of all phases of the barium puff releases on 9 March.

2. Magnetic Observations

The DEVELCO cryogenic magnetometer worked exceedingly well under adverse field-site conditions. Data were recorded on magnetic tape at times of interest, as indicated earlier in Section III. In addition, magnetic variations were recorded on chart paper in real time

19

FIGURE 3 AURORAL DISPLAY ABOVE VENETIE AT APPROXIMATELY 0730 GMT, 7 MARCH 1972

20

to verify that the instrument continued to operate properly. The full 80-Hz bandwidth of the data was preserved on magnetic tape, while the bandwidth of the chart data was only 2 Hz. The magnetic variations at times spanning the OOSIK release are shown in Figure 4. This plot was prepared from the chart data before the magnetic-tape data were processed. A relatively slow magnetic excursion of 130 γ is evident between 0520 and 0620 GMT. In the 40 min before the OOSIK release a very gradual recovery was underway with rapid fluctuations of less than ± 10 γ. The slow recovery continued through launch and release until 0715:48 GMT, at which time a sudden commencement initiated a rapid excursion of 275 γ by 0723:20 GMT. There is some error in the plotted data in Figure 4 during the rapid deflection, due to the slow response of the chart recorder; the values quoted here are from an analysis of the tape data. A recovery of 49 γ occurred by 0725:15 GMT only to be followed by a very rapid additional excursion of 93 γ. The maximum excursion from the precommencement value was 320 γ, and it was reached at 0727:00. In evaluating this peak excursion we should remember that the axis of the sensing coil was at 45° elevation and 45° from the magnetic meridian.

The initial positive phase of the magnetic perturbation lasted approximately 20 min and was followed by a negative phase of about one hour duration. The maximum excursion during this period was about 170 γ. The final characteristic of interest shown in Figure 4 is the oscillatory behavior near 0900 GMT. The period of oscillation is about 360 s, corresponding to a PC5.

The magnetic behavior that followed the OOSIK release by 17 min is very impressive. However, its association with the OOSIK event is questionable for at least two reasons. Investigation[10] by the University of Alaska has shown that magnetometer records from Hawaii indicate the
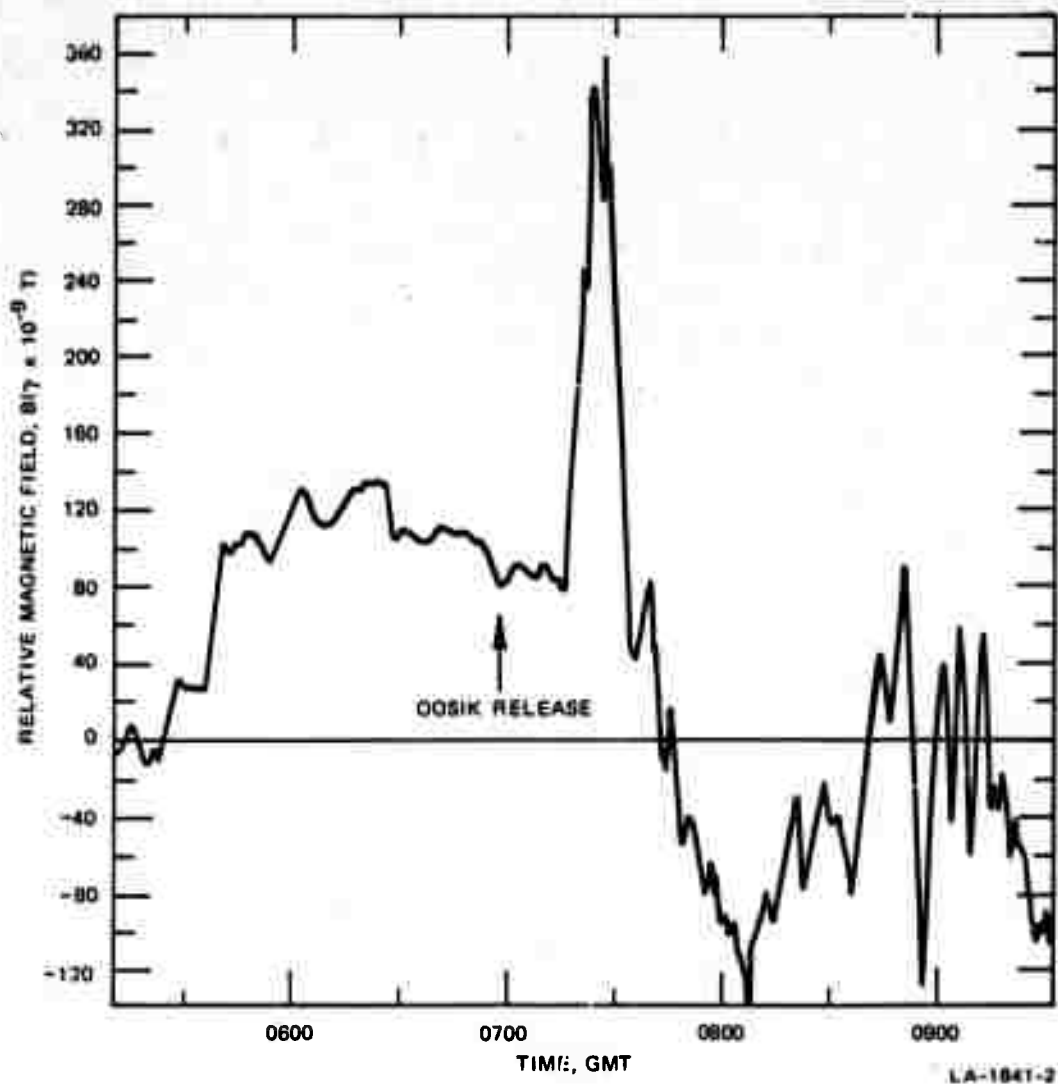
21

FIGURE 4 MAGNETIC VARIATIONS AT VENETIE AT TIMES SPANNING THE
OOSIK RELEASE

onset of a substorm nearly two hours before the OOSIK release. Magnetic perturbations were not confined to the central Alaska area; they were observed over most of western Canada as well.

Magnetometer data recorded on tape during the three series of barium puff releases have not been investigated.

3. Radio-Noise Observations

Three data tapes recorded in the interval 0606 to 0920 GMT on March 7 have been analyzed in search of changes in signal character. A variety of spectrum analyzers were utilized to produce frequency-vs-time film displays intensity-modulated by the spectral amplitude. Greatest emphasis was given to the frequency band from a few hundred hertz to about 10 kHz, although the entire 100 kHz of the broadband system was considered. No discrete noise bursts were associated with either the rocket launch or the barium release, nor were there any recognizable changes in the noise background for two hours following the release. The evaluation of noise background is somewhat complicated by the presence of local power-generation-system noise up to well above 1 kHz, and by intermodulation products of some of the stronger signals from VLF and LF transmitters.

The negative findings of the broadband data are confirmed by the spectral data from the satellite receiver. These data were displayed on film in a comparable manner and show no recognizable change in signal.

B. Radar Observations at Homer

The radar at Homer began operation at 0653 GMT on March 7, virtually coincident with launch of the rocket carrying the OOSIK shaped charge. From this time until 0714 GMT the antenna was directed almost continuously at an elevation of 3° and an azimuth of 15° to monitor the lower ionosphere in the vicinity of the down-field location of the anticipated

release. Frequent azimuth and elevation sweeps were used at later times to define the location of auroral returns. Data tapes recorded at times of interest have been processed to obtain range-time-intensity (RTI) displays. The 139-MHz auroral returns observed on the RTI displays have been combined with azimuth information at specific times to obtain the geographic coverage plots in Figures 5 through 10. The E-region intercept of the magnetic field line through the barium release is indicated by an asterisk.

The following is a summary of radar returns received at Homer during times spanning the OOSIK release:

- **0653:50 to 0654:45 GMT, Elevation 3°, Azimuth 16°**
  - Signals returned from a range of 600 and 700 km were very weak.
  - Signals returned from a range of 950 km were weak, while signals from 1080 km were somewhat stronger.

- **0654:45 to 0655:40 GMT, Elevation 3°, Azimuth Scan**
  - The location of signal returns is shown in Figure 5.
  - The signal returned from ranges of 1050 to 1100 km was strongest.
  - The ionosphere directly below the nominal barium-release location and down the field from it was free of radar auroral returns.

- **0655:40 to 0.01 GMT, Elevation 3°, Azimuth 16°**
  - Weak signals present during most of this period decreased in range from 725 to 650 km.
  - Signals returned from ranges of 1050 and 1125 km early in this period vanished by 0657:40. The signal from 1050 km grew in strength after 0659 GMT when the barium was released, and was clearly evident at 0701.
  - Signals returned from 925 and 1125 km became evident soon after the release.
  - Signals that grew in strength following the barium release originated at ranges at least 50 km north of the down-field ionospheric intercept of the release point.
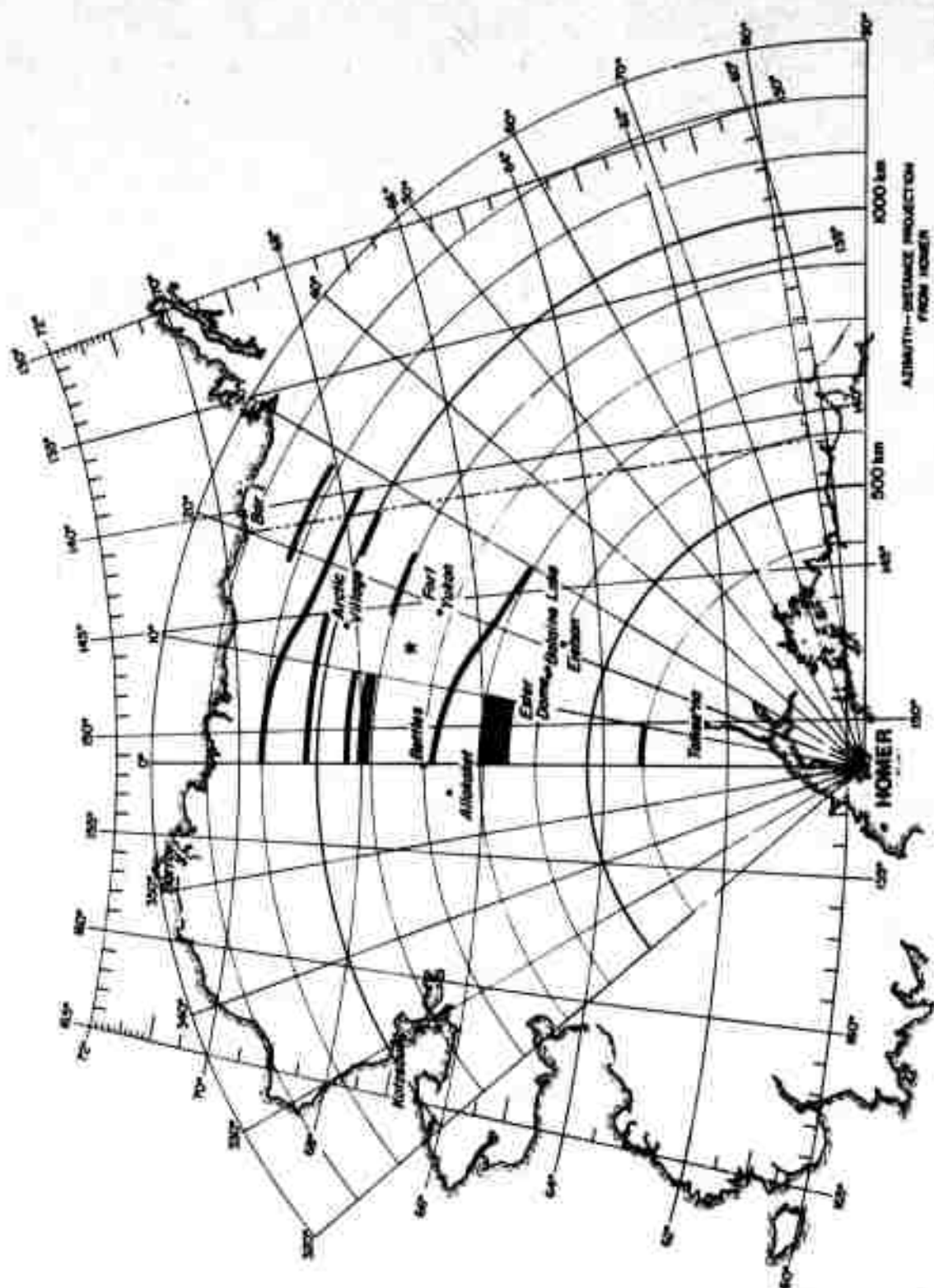
24

FIGURE 5   RADAR AURORA OBSERVED AT HOMER, ALASKA AT 0855 GMT, 7 MARCH 1972 — AZIMUTH SCAN
AT 3° ELEVATION

25

FIGURE 6   RADAR AURORA OBSERVED AT HOMER, ALASKA AT 0702 GMT, 7 MARCH 1972 — AZIMUTH SCAN
AT 3° ELEVATION

FIGURE 7   RADAR AURORA OBSERVED AT HOMER, ALASKA AT 0707 GMT, 7 MARCH 1972 — ELEVATION SCAN AT 16° AZIMUTH

FIGURE 8   RADAR AURORA OBSERVED AT HOMER, ALASKA AT 0716 GMT, 7 MARCH 1972 — AZIMUTH SCAN
AT 3° ELEVATION

28
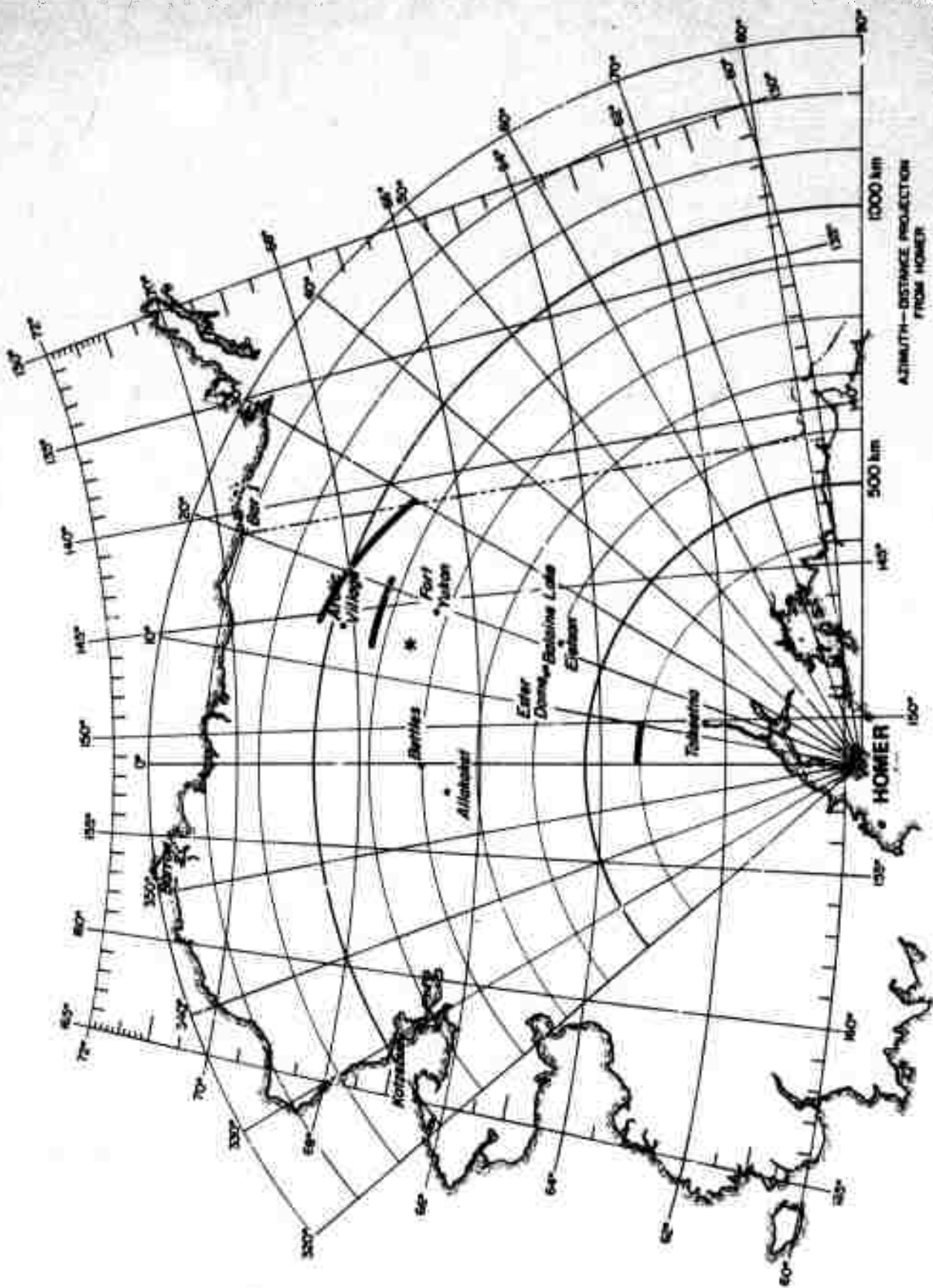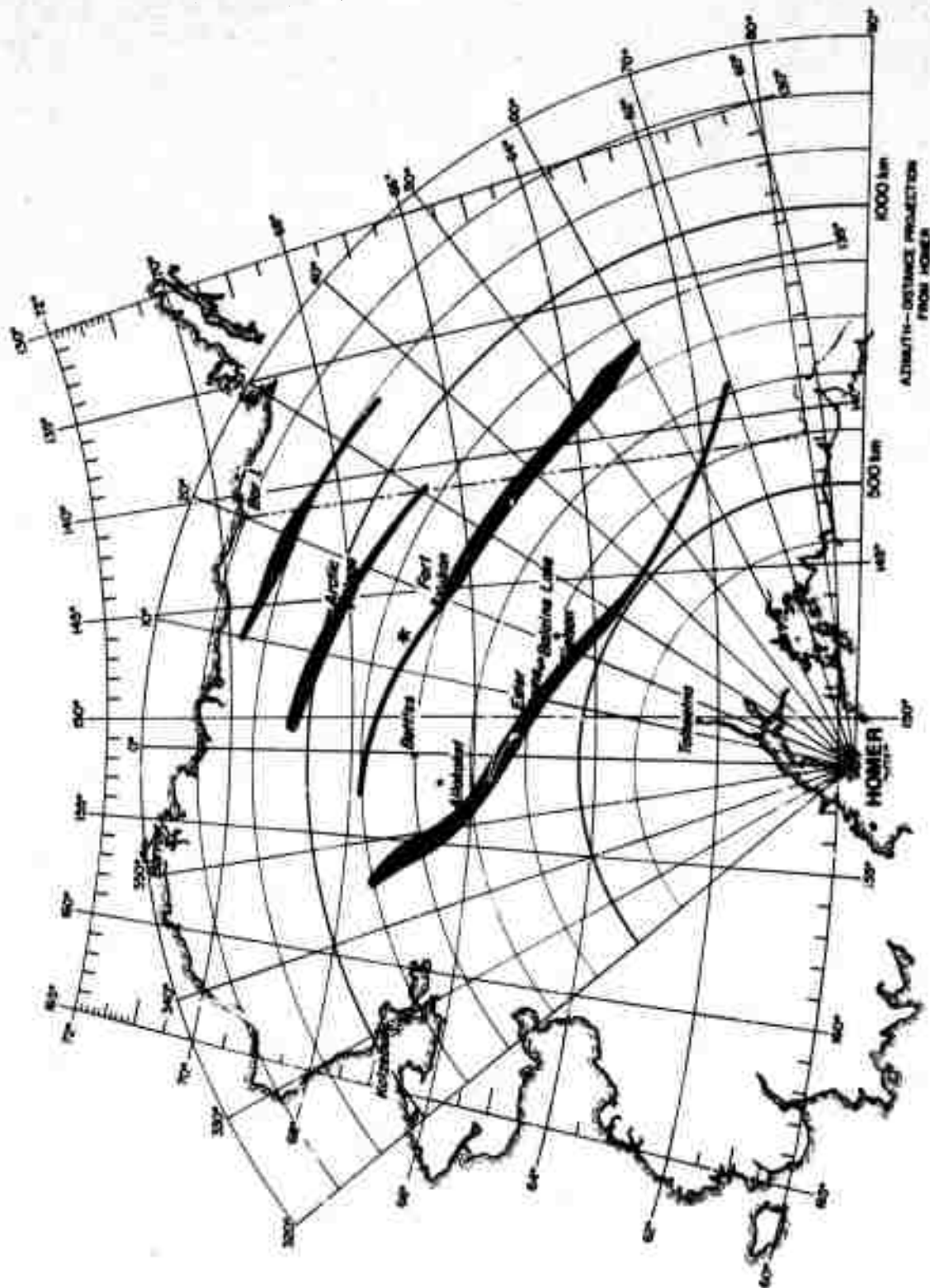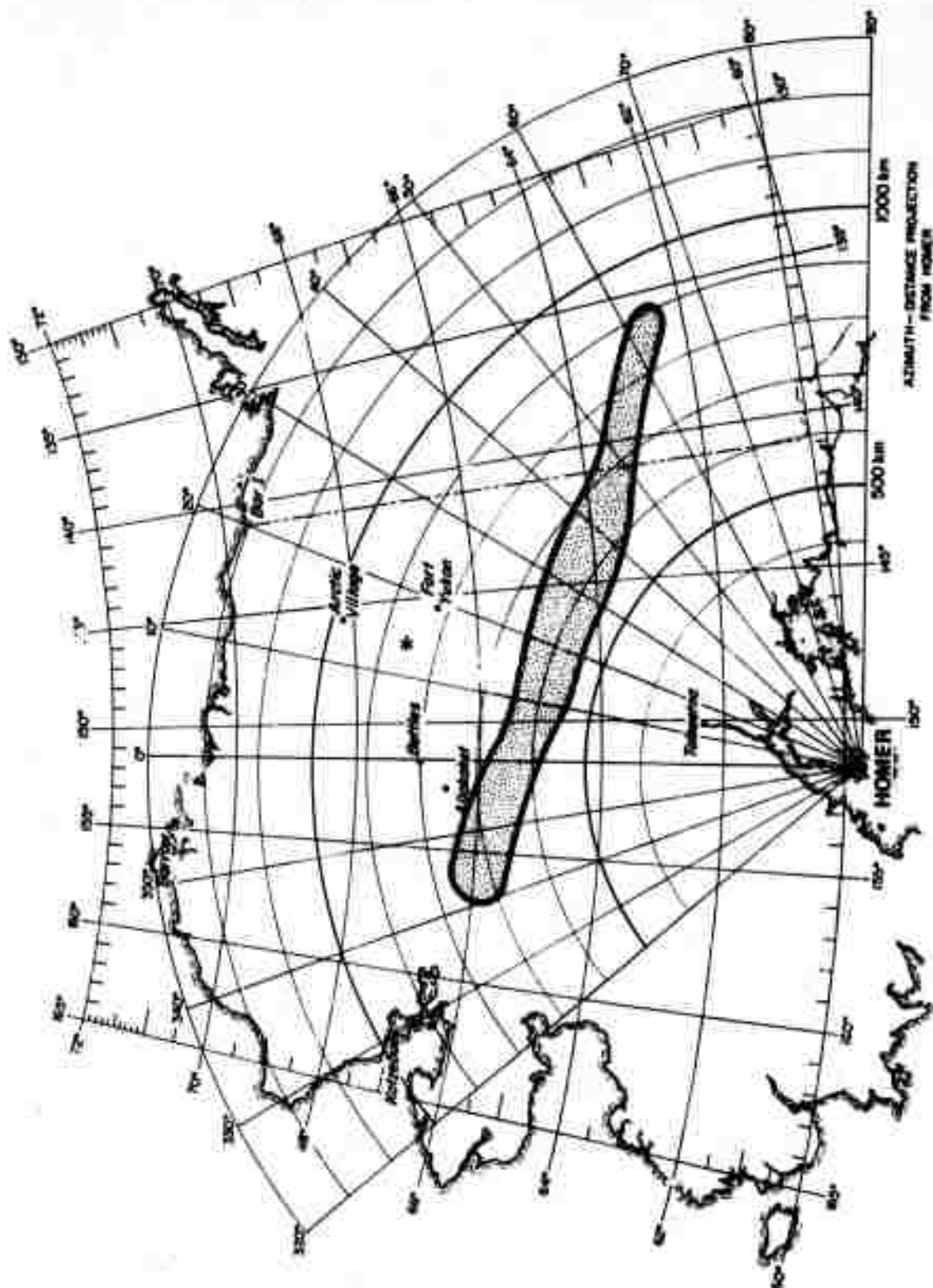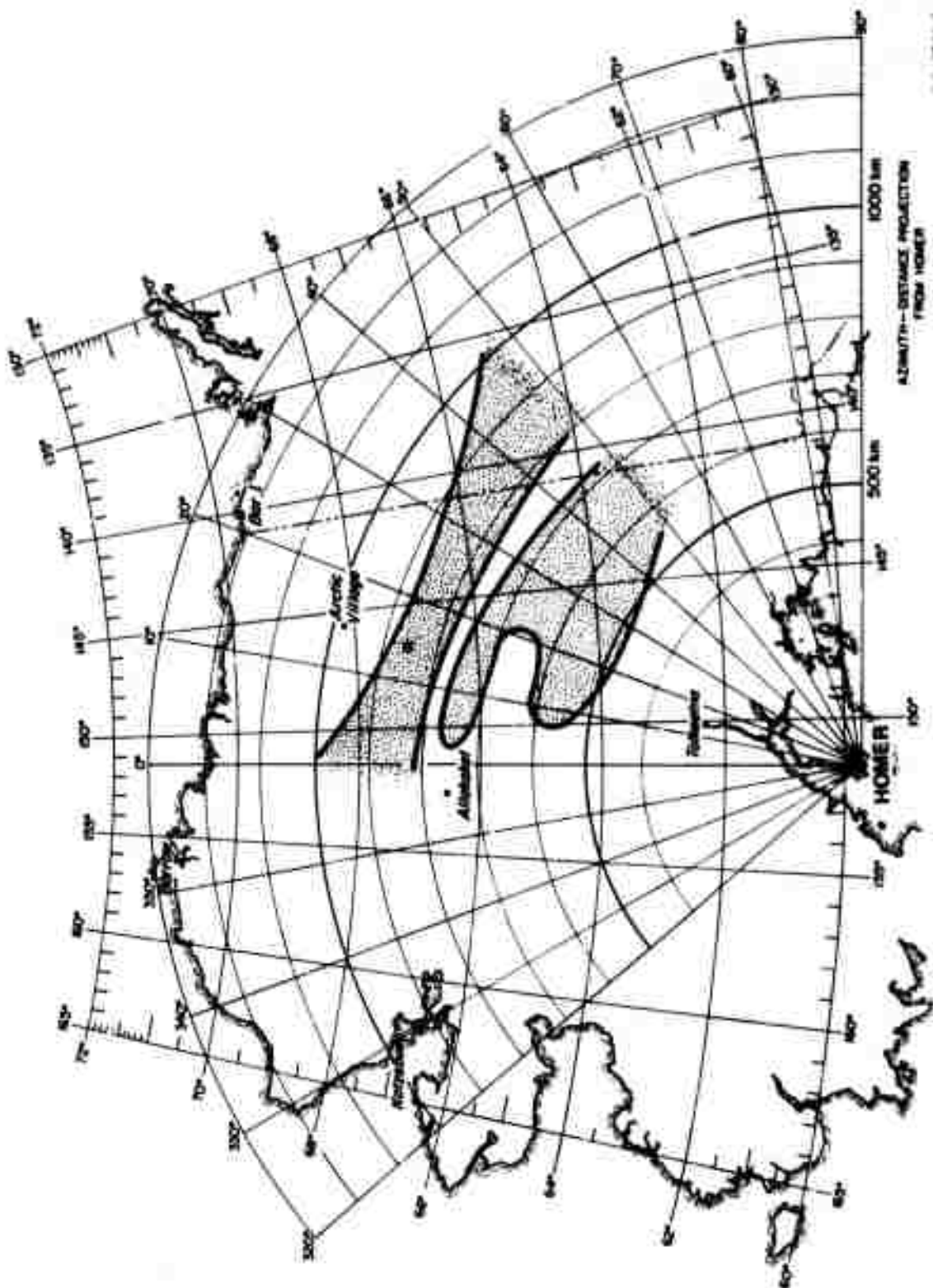
FIGURE 9   RADAR AURORA OBSERVED AT HOMER, ALASKA AT 0718 GMT, 7 MARCH 1972 — AZIMUTH SCAN AT 5° ELEVATION

LA-1841-7

29

FIGURE 10   RADAR AURORA OBSERVED AT HOMER, ALASKA AT 0725 GMT, 7 MARCH 1972 — AZIMUTH SCAN AT 6° ELEVATION

30

- 0701 to 0702:50 GMT, Elevation 3°, Azimuth Scan

  - Radar returns received during the azimuth scan are shown in Figure 6.

  - The ionosphere directly below the actual barium-release location and down the field from it were free of radar auroral returns.

- 0702:50 to 0705:45, Elevation 6°, Azimuth 16°

  - Note that a change in elevation from 3° to 6° favors auroral returns at 700 km range rather than 900 km range.

  - Weak signal returned from 650, 875, and 1050 km were present during most of the period.

  - The return from 875 km came from the vicinity of the down-field ionospheric intercept of the barium release.

- 0705:45 to 0707:40, Elevation Scan, Azimuth 16°

  - Radar returns received during the elevation scan are shown in Figure 7.

  - Magnetic flux tubes populated by barium ions moved south and east following release. Their ionospheric intercept apparently was free of radar returns during this elevation scan.

- 0707:40 to 0713:50 GMT, Elevation 6°, Azimuth 16°

  - Radar returns from 550 km and 1000 km decreased in range to 475 and 900 km during this period.

  - The ionospheric intercept of populated flux tubes was free of radar returns.

- 0713:50 to 0727 GMT, Frequent Elevation and Azimuth Scans

  - Radar returns at 0716, 0718, and 0725 are shown in Figures 8, 9, and 10.

  - Four fairly discrete radar auroral areas were present at 0716 less than a minute after onset of the magnetic substorm.

  - The ionospheric intercept of populated flux tubes still appeared to be free of radar returns.

- At 0718 the more distant radar aurora had disappeared and a 100-km-wide belt of more than 1000 km length lay above Fairbanks. The ionospheric intercept of populated flux tubes probably lay within this region of radar returns.

- By 0725 GMT radar returns were received from nearly all ranges between 500 and 1000 km.

- **0727 to 0830 GMT, Elevation 6°, Azimuth 16°**

  - Radar returns were received from nearly all ranges between 500 and 1000 km.

The correlation between radar and visual aurora was not particularly good prior to the magnetic disturbance. At times from 0655 to 0716 there were radar targets at locations that would be visible from Venetie, yet all of the visible aurora was far to the south. The location of radar aurora at 0718 and 0725 is in good agreement with the visual aurora.

C. Radar Observations at Chatanika

The Chatanika incoherent-scatter radar performed a number of measurements during times spanning the OOSIK shaped-charge release. The following are the times (GMT) at which various operating modes were used:

- 0416 to 0445   Vector velocity--three-position scan
- 0446 to 0455   Expected release point of barium puffs--background
- 0455 to 0516   Vector velocity--only two or three positions
- 0516 to 0526   Expected release point of barium puffs--elevation scan
- 0527 to 0606   East-west velocity
- 0607 to 0637   Vector velocity--three-position scan
- 0641 to 0649   F-region, down field line from expected OOSIK release point
- 0652 to 0659   Expected OOSIK release point
- 0700 to 0705   Scans in vicinity of OOSIK release

- 0705 to 0708   F-Region down field from expected OOSIK release point
- 0709 to 0729   East-west velocity
- 0731 to 0851   Magnetic zenith.

During the time period when the expected OOSIK release point was monitored, echoes from the carrier rocket and many of its fragments were obtained, complicating the analysis of the data. In addition, post-mission analysis has shown that the antenna beam was pointed a few tens of kilometers away from the actual release point. No unusual ionospheric returns were obtained from the vicinity of the release point. Figure 11 shows profiles of electron densities and electron and ion temperature obtained during this time period.

Comparison of pre- and post-release electron-density profiles from the F-region down the earth's field line from the expected release point shows no unusual ionization attributable to the OOSIK release. These profiles are shown in Figure 12. The pre-release profile does, however, show an unusual "blob" of ionization at an altitude of 170 km that did not appear on any of the other electron-density profiles.

The plasma-velocity measurements showed high magnetic east-west velocities which changed significantly in direction and magnitude during the 4-hour period 0430 to 0830 GMT. Figure 13 shows the velocity-measurement results for an altitude of approximately 300 km. All components of velocity are not available at all times because of changes in operating modes at various times during the evening. The most striking feature of Figure 13 is the large westward F-region velocities which persisted until about an hour before release. Moderate ($\sim$ 200 m/s) eastward velocities were present until about a half hour after release, after which 500-m/s westward velocities were again seen. These large velocities, coupled with the reversal at about 0730, were probably instrumental in causing the OOSIK release to break up into multiple striations. During
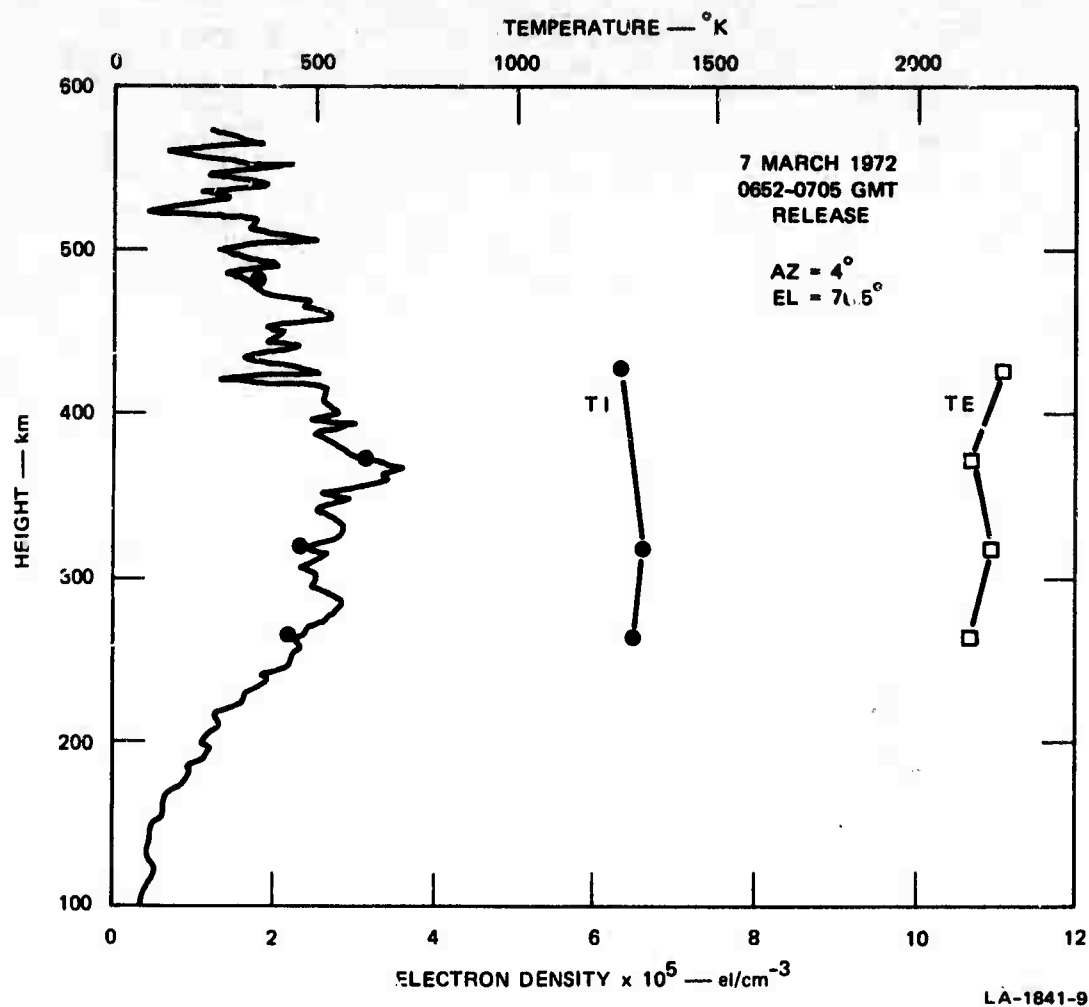
33

FIGURE 1‘ PROFILES OF ELECTRON DENSITY AND ELECTRON AND ION TEMPERATURE OBTAINED WITH THE ANTENNA POINTED TOWARD THE VICINITY OF THE OOSIK RELEASE — 0652 TO 0705 GMT

PRE-RELEASE
(F-REGION)
0641-0647 GMT
7 MARCH 1972

AZ = 10°
EL = 63.5°

POST-RELEASE
(F-REGION)
0705-0708 GMT
7 MARCH 1972

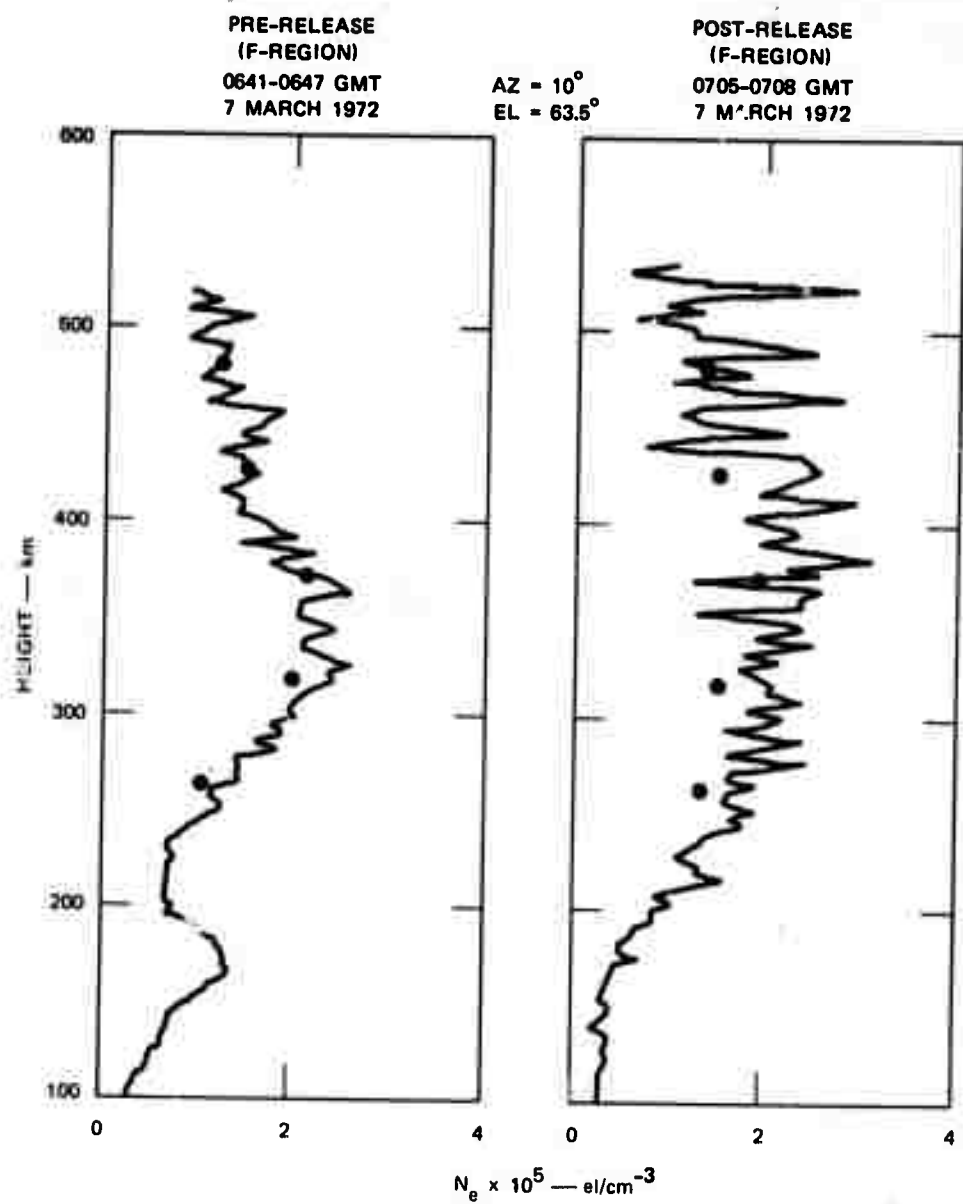$N_e \times 10^5$ — el/cm^{-3}

LA-1841-10

FIGURE 12   PRE- AND POST-RELEASE ELECTRON-DENSITY PROFILES OBTAINED
WITH THE ANTENNA POINTING AT THE F-REGION DOWN THE EARTH'S
MAGNETIC FIELD LINE FROM THE EXPECTED OOSIK RELEASE POINT

35
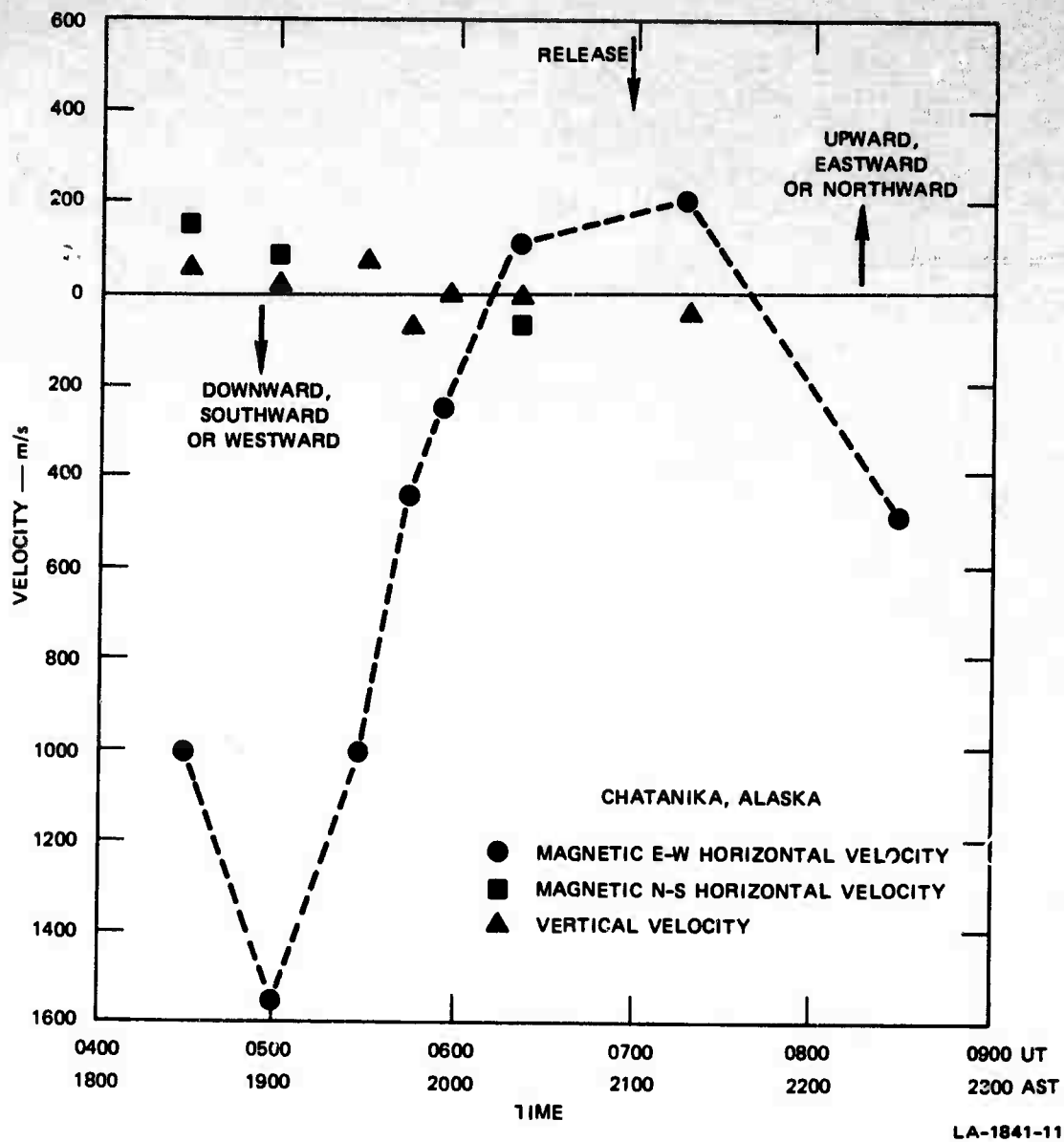
FIGURE 13   F-REGION PLASMA VELOCITIES — 0430 TO 0830 GMT, 7 MARCH 1972

36

the entire period the north-south and vertical velocities were fairly low (100 m/s or less). However, if one considers the meridional component of velocity perpendicular to the earth's magnetic field, it appears that this component reversed direction (from northward to southward) at about the same time (~ 0605 GMT) that the east-west component reversed. Thus, at release and shortly thereafter, the F-region plasma was drifting eastward at about 200 m/s and southward at about 100 m/s or so.

VI EVALUATION OF DATA

There are three possible explanations of the OOSIK data; they are:

(1) The magnetic substorm and auroral display following OOSIK were triggered by the barium release.

(2) A natural magnetic substorm occurred following OOSIK and masked effects of the barium release.

(3) A natural magnetic substorm occurred. There were no effects of the OOSIK barium release.

Of the three, the first seems unlikely; the second is possible, but the third is probably the true explanation. We have already stated that the substorm and aurora were observed over a wide geographic area, highly indicative of natural origin. A quantitative review of the most recent developments[2] in plasma-injection theory will indicate the wisdom of the third explanation over the second.

The central concept in magnetospheric plasma-injection experiments is that the density of cold* plasma influences the flux of hot+ plasma that can remain stably trapped in the earth's magnetic field. According to Brice and Lucas,[2] there is a finite limit to the flux of hot electrons whose energy parallel to the earth's magnetic field exceeds

$$E_{\parallel} = B^2/[2\ \mu_o\ N_{\infty}A(A+1)^2]$$

where B is the local magnetic field strength, μ_o is the permeability of

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*Cold plasma—electron energies in the hundred-electron-volt range.

+Hot plasma—electron energies in the kiloelectron-volt range.

free space, N_∞ is the density of cold electrons, and A is the energy anisotropy of hot electrons (all in MKS units). We see from the equation that an increase in N_∞ leads to a decrease in $E_\parallel$, imposing a limit on the flux of a group of electrons that had previously not been limited. If the flux of this group of electrons exceeds the newly imposed limit, then a plasma instability occurs in which the excess electrons are precipitated into the atmosphere as a result of pitch-angle redistribution. In the course of redistribution, low-frequency waves propagating along the field are amplified.

To calculate the cold-plasma density required to precipitate electrons of a given energy the equation in the previous paragraph can be rearranged as follows:

$$N_\infty = B^2 / [2 \; \mu_o \; E_\parallel A(A + 1)^2] \qquad .$$

Three examples illustrate the range of cold-plasma density required to trigger an instability in various ambient magnetospheres. These are as follows:

- Case 1
    - L value, 6.75
    - Magnetic-field strength in the equatorial plane, 102 γ
    - Energy of electrons to be precipitated, 40 keV
    - Anisotropy of electrons (A), 1/2
    - Parallel energy of electrons ($E_\parallel$), 10 keV
    - Maximum cold-plasma density (N_∞) that will support infinite flux, 2.3 el cm^{-3}.

    The parameters of this example are intended to represent magnetospheric conditions during the early morning, the most ideal time for an injection experiment.

- Case 2

    - L value, 6.75

    - Magnetic-field strength in equatorial plane, 102 γ

    - Energy of electrons to be precipitated, 10 keV

    - Anisotropy of electrons (Λ), 1/2

    - Parallel energy of electrons ($E_\parallel$), 2.5 keV

    - Maximum cold-plasma density (N_∞) that will support
      infinite flux, 9.2 el cm^{-3}.

    The parameters of this example are intended to represent
    favorable magnetospheric conditions at night.

- Case 3

    - L value, 6.75

    - Magnetic-field strength in the equatorial plane, 102 γ

    - Energy of electrons to be precipitated, 1 keV

    - Anisotropy of electrons (A), 1/10

    - Parallel energy of electrons ($E_\parallel$), 5/16 keV

    - Maximum cold-plasma density (N_∞) that will support
      infinite flux, 680 el cm^{-3}.

    The parameters of this example are intended to represent
    unfavorable magnetic conditions at night.

The cold-plasma densities, 2.3, 9.2, and 680 el cm^{-3} calculated for the
three examples support infinite flux at the specified electron energies.
Cold-plasma densities perhaps 10 percent higher should begin to precipi-
tate hot electrons, thus raising the threshold to 2.5, 10, and 750 el cm^{-3}
for these three examples. In actual practice it may require two to four
times the threshold cold-plasma density to achieve significant precipita-
tion. The ambient cold-plasma density at L = 6.75 varies from about 0.1
to 10 el cm^{-3}, depending on magnetospheric conditions.

In estimating the barium plasma density reaching the equatorial
plane following OOSIK we must rely on Murcray's[7] discussion of the

BARBIZON events in October 1971. Hc estimates the following distribution of barium-ion energies:

- Less than 10 eV 1.2×10^{24} ions, less than 3.3 km/s
- Greater than 10 eV 1.8×10^{24} ions, greater than 3.3 km/s
- 100 to 150 eV 0.6×10^{24} ions, 10.54 to 12.91 km/s
- 150 to 160 eV 0.6×10^{24} ions, 12.91 to 13.33 km/s.

The diameter of the jet soon after its formation was about 5 km, corresponding to a cross section of 19.6 km^2. Consider first the volume filled by the 150-to-160-eV energy group when they reach the equatorial plane. The cross-sectional area of the populated flux tube at the point of release scales as the ratio of magnetic flux densities in extrapolating up the field line to the equatorial plane. From a multicoefficient model of the earth's field this ratio has been determined to be 440, giving a cross section at the equatorial plane of 8,600 km^2. The effective length of the flux tube populated by the 150-to-160-eV group is not easily estimated because of the spiral path followed in ascending the field and because of the altitude variation in the gravitational influence. If both these effects are ignored, the energy spread of 10 eV corresponds to a spatial spread of 1,500 km in traveling 53,100 km to the top of the field. Let us account for the influence of gravity and for the spiral path by using a populated length of 10,000 km. The volume is 8.6×10^{22} cm^3, giving an average density of 7 el cm^{-3}. This density is sufficient to trigger a magnetospheric instability under favorable morning conditions; it is probably not sufficient to trigger an instability in the evening when OOSIK was launched. Furthermore, we must remember that eight or more separate field lines were observed to be populated, so that the density at the top of the field line more than an hour after release may not have been much more than 1 el cm^{-3}.

VII CONCLUSIONS AND RECOMMENDATIONS

Two general conclusions have been reached:

(1) Shaped barium charges of the type released in Alaska
    in March 1972 appear capable of injecting sufficient
    cold plasma into the magnetosphere to cause instability
    under favorable morning magnetospheric conditions.

(2) The shaped barium charge release in Alaska in March 1972
    probably did not produce a magnetosphere instability.

Conclusion 1 is based on a comparison of plasma densities required
for instability and those that seem likely to be achieved by a shaped-
charge release. From the formulations of Brice and Lucas we have
deduced that an equatorial cold-plasma density in excess of 2.5 el cm^{-3}
is required to initiate an instability during favorable morning conditions,
while at night a density in excess of 10 el cm^{-3} is required. Significant
instabilities probably can be achieved with densities two to four times
these threshold values. Densities perhaps as great as 10 el cm^{-3} may be
achieved by shaped-charge releases. The degradation due to striation of
barium has not been considered.

Conclusion 2 is based on a comparison of density required for in-
stability at the time of release and the density actually thought to have
been achieved. The evening release would have had to populate the equa-
torial portion of the field to a density in excess of 10 el cm^{-3}. Because
of the spreading of barium ions to a number of different field lines the
density achieved on any one of them probably was not much greater than
1 el cm^{-3}. The magnetic substorm and auroral activity observed soon
after the barium release appear to be of natural origin; they occur before
the barium ions had ascended more than one-third of the way up the field.

Instabilities are most likely to occur near the top of the field. The dramatic auroral display at the magnetic zenith of Venetie did occur in the general vicinity of the release, but at a time when the populated magnetic flux tubes had moved far to the south and east.

The following actions are recommended:

(1) The mechanism that caused the OOSIK barium jet to break up into a number of different flux tubes should be identified. Breakup probably prevented the density in any one flux tube from exceeding a value necessary to initiate an instability.

(2) Additional measurements should be conducted during shaped-charge releases planned for Alaska in October 1972 and the spring of 1973. The degree of experimental investigation would be contingent upon recommendation of the ARPA panel investigating the feasibility and applicability of magneto-spheric instability. Existing radars, magnetometers, and satellites could provide modest coverage, while a thorough investigation could make use of additional field sites and rocket-borne instrumentation.

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